THE NONLINEAR-ELECTRODYNAMIC BENDING OF THE X-RAY AND GAMMA-RAY IN THE MAGNETIC FIELD OF PULSARS AND MAGNETARS *

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ABSTRACT

It was shown that according to the non-linear electrodynamics of vacuum electromagnetic rays should bend in the field of magnetic dipole. The angles of ray bending in the gravitational and magnetic fields of pulsars and magnetars were obtained. In the case of pulsars with $b \sim R \sim 100$ km, $B_0 \sim 10^{13}\ G$ the value of the angle of non-linear electrodynamic bending of a ray in the Heisenberg-Euler theory will reach the value of $\delta\psi_{NED} \sim 30''$, and in the case of a magnetar with $B_0 \sim 10^{15}\ G$ the angle $\delta\psi_{NED}$ will increase to $\delta\psi_{NED} \sim 1\ rad \sim 60^\circ$. The angle of gravitational bending of a ray at neutron star with $r_g = 3$ km in the same conditions will be equal to $\delta\psi_g \sim 0.06$ rad $\sim 4^\circ$. Observations can only be made in X- rays and gamma-rays, for which the magnetosphere is quite opaque. Because the distance from the Earth to the well-known pulsars and magnetars is too large to observe the pure effect of a ray bending. The non-linear electrodynamic bending of a ray as well as the gravitational bending will be revealed in the effect of lensing.

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As it is well-known, the Maxwellian electrodynamics in the absence of matter is a linear theory. Its predictions concerning a very wide field of problems (except the subatomic level) are constantly confirmed with better and better accuracy. Quantum electrodynamics, which is based on Maxwell's electrodynamics complemented by the renormalization procedure, also describes with good accuracy the various subatomic processes, and, according to common opinion, is one of the best physical theories.

However, some fundamental physical reasons indicate that electrodynamics is nonlinear not only in continuous medium, but in vacuum also.

Several different models of non-linear electrodynamics of vacuum are discussed now in the field theory. In the case of a weak fields their Lagrangian can be written in the parameterized form [1,2]:

$$L = \frac{1}{8\pi}\Big\{[\mathbf{E}^2 - \mathbf{B}^2] + \xi[\eta_1(\mathbf{E}^2 - \mathbf{B}^2)^2 + 4\eta_2(\mathbf{B}\ \mathbf{E})^2]\Big\}, \tag{1}$$

where $\xi = 1/B_q^2$, $B_q = 4.41 \cdot 10^{13}\ G$, and the value of dimensionless post-Maxwellian parameters η_1 η_2 depends on the choice of the model of non-linear electrodynamics in vacuum.

In particular, the η_1 and η_2 parameters in the Heisenberg-Euler non-linear electrodynamics have quite concrete values $\eta_1 = \alpha/(45\pi) = 5.1 \cdot 10^{-5}$, $\eta_2 = 7\alpha/(180\pi) = 9.0 \cdot 10^{-5}$, while in the Born-Infeld theory they can be expressed through the unknown constant $a^2 : \eta_1 = \eta_2 = a^2 B_q^2/4$.

The equations of electromagnetic field in the non-linear electrodynamics are analogous to the equations of electrodynamics of continuous medium:

$$curl\ \mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t}, \quad div\ \mathbf{D} = 0, \quad \mathbf{D} = 4\pi\frac{\partial L}{\partial \mathbf{E}},$$

$$curl\ \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \quad div\ \mathbf{B} = 0, \quad \mathbf{H} = -4\pi\frac{\partial L}{\partial \mathbf{B}}.$$

Using expression (1), it is not difficult to obtain the expansion of vectors $\mathbf{D}$ and $\mathbf{H}$ in degrees B/B_q and E/B_q with the first order of post-Mawellian accuracy:

$$\mathbf{D} = \mathbf{E} + 2\xi\{\eta_1(\mathbf{E}^2 - \mathbf{B}^2)\mathbf{E} + 2\eta_2(\mathbf{B}\ \mathbf{E})\mathbf{B}\},$$

$$\mathbf{H} = \mathbf{B} + 2\xi\{\eta_1(\mathbf{E}^2 - \mathbf{B}^2)\mathbf{B} - 2\eta_2(\mathbf{B}\ \mathbf{E})\mathbf{E}\}.$$

During a long time, the non-linear electrodynamics of vacuum had no experimental confirmation and, hence, it seems for many researchers as only abstract theoretical model. At present its status has changed drastically. The

experiments on non-elastic scattering of laser photons on gamma- quanta [3] confirm the non-linear character of electrodynamics in vacuum. Thus, its different predictions [4 -10], which can be tested experimentally, are of great importance. However, non-linear corrections to the Maxwell equations for the magnetic fields $B,\ E \sim 10^6$ G, which can only be obtained in ground laboratories, are too small to observe effects caused by them. On the other hand, some objects are existing in nature, in which magnetic field induction is comparable with the typical value of magnetic field induction required for essential manifestation of electrodynamics non-linearity in vacuum $B \sim 4.41 \cdot 10^{13}$ G, which was predicted by quantum electrodynamics.

These objects are rotation-powered pulsars and magnetars. Rotation-powered pulsars are rapidly-rotating neutron stars with a strong dipole magnetic field

$$\mathbf{B}_0 = \frac{3(\mathbf{m} \cdot \mathbf{r})\mathbf{r} - r^2\mathbf{m}}{r^5},$$

where $\mathbf{m}$ is the magnetic dipole momentum.

Most of them are the so-called "radio" pulsars, i.e. isolated neutron stars, the emission of which is powered by the loss of rotational energy [11]. The high sensitivity of modern X-ray observatories permits to detect X-rays from about several dozens of radio pulsars [12], but only ten (or possibly six) rotation-powered pulsars were observed at gamma-ray energies, i.e. so-called "gamma"- pulsars [13]. Most of them have a rather strong surface magnetic field ($max\ B_0 \geq 10^{12}$ G), for at least five gamma-pulsars the magnitude of B_0 exceeds the characteristic value of $4.41 \cdot 10^{13}$ G [13]. Although, it is not yet clear how and where in the pulsar magnetosphere the non-thermal high-energy emission originates, several advanced models assume that particles are accelerated above the neutron star surface and that gamma-rays result from curvature radiation or inverse Compton induced pair cascade in a strong magnetic field near the neutron star, i.e. the so-called "polar cap" models [14-18]. These models give the opportunity to observe nonlinear electrodynamics effects in gamma-pulsar hard emission.

As for magnetars, or strongly magnetized neutron stars [19-22], they are the most appropriate sources for manifestation of nonlinear electrodynamics effects. It is supposed now that magnetars can be revealed as soft gamma-ray repeaters (SGR) mainly observed in hard X-rays and soft gamma rays [23] and as so-called anomalous X-ray pulsars (AXP), i.e. slow (6-12 s period) rotators mainly observed in the "classical" X-ray range (2-20 keV) [24]. SGRs are transient events characterized by brief (≤ 1 s) and relatively soft (peak photon energy $\sim 10 - 30$ keV) bursts of super- Ed-

dington luminosity. There are four (or five) SGRs known now. A possible connection between SGR and AXP was suggested after the discovery of periodicities as well as spin-down effect in some SGRs [25,26] with the values of period and period derivative very similar to those of AXP. Another similarity between SGR and AXP is based on the fact that all of them appear to be associated with supernova remnants (SNRs). The magnetic field B magnitude in such objects can be estimated from the period and period derivative values, which lead to $max\ B_0 \geq 10^{14} - 10^{15}$ G. In most of the magnetar models the magnetic field is the main energy source, powering both the persistent X-ray emission and the soft gamma-ray burst activity.

Thus, non-linear electrodynamic effects will be much more pronounced in the dipole magnetic fields of gamma-ray pulsars and magnetars than in any ground laboratory experiments.

The non-linear electrodynamic bending of electromagnetic wave rays in the magnetic fields of pulsars and magnetars is one of such effects. As it can be seen from simple calculations [27], the bending angle $\delta\psi$ of a ray in the gravitational and magnetic field of a neutron star depends on the mutual orientation of a ray and the star magnetic dipole momentum $\mathbf{m}$ as well as on the electromagnetic wave polarization.

In particular, for an electromagnetic wave, propagating in the neutron star magnetic equator plane and polarized in the same plane, the bending angle of a ray will be:

$$\delta\psi = \frac{2r_g}{b} + \frac{15\pi\eta_1\xi B_0^2 R^6}{4b^6},$$

where r_g is the Schwartzhield radii of a star, R is the star geometrical radii, B_0 is the induction of the magnetic field on the star magnetic equator.

For an electromagnetic wave polarized normally to the magnetic equator, one can obtain:

$$\delta\psi = \frac{2r_g}{b} + \frac{15\pi\eta_2\xi B_0^2 R^6}{4b^6}.$$

Thus, the angle of non-linear electromagnetic bending of a ray $\delta\psi_{NED} = 15\pi\eta_{1,2}\xi B_0^2 R^6/(4b^6)$ depends on the impact distance b differently than the angle of gravitational bending of a ray $\delta\psi_g = 2r_g/b$. Besides, at $\eta_1 \neq \eta_2$ the angle $\delta\psi_{NED}$ depends on the electromagnetic wave polarization, and the angle $\delta\psi_g$ does not. Thus, these two parts of the total angle of ray bending can be revealed by the processing of sufficiently complete observational

data, obtained for the different values of impact distance b and different polarizations of the electromagnetic wave.

In the case of a pulsar with $b \sim R \sim 100$ km, $B_0 \sim 10^{13}$ G value of the angle of non-linear electrodynamic bending of a ray in the Heisenberg-Euler theory will reach the value $\delta\psi_{NED} \sim 30''$, and in the case of a magnetar with $B_0 \sim 10^{15}$ G the angle $\delta\psi_{NED}$ increases to $\delta\psi_{NED} \sim 1\ rad \sim 60°$.

For comparison, we can indicate that the angle of gravitational bending of a ray a neutron star with $r_g = 3$ km under the same conditions will be equal $\delta\psi_g \sim 0.06$ rad $\sim 4°$.

However, it is rather difficult to observe this effect. Firstly, both pulsars and magnetars have a sufficiently dense magnetosphere. Thus, observations can be made only in the X- rays and gamma-rays, for which the magnetosphere is quite opaque.

Secondly, the distance from the Earth to the well-known pulsars and magnetars is too large to observe the pure effect of a ray bending

As our analysis shows [27], the non-linear electrodynamic bending of a ray as well as the gravitational bending will be revealed in the effect of lensing. As a result, the external manifestations of effects of non-linear electrodynamic and gravitational bending of a ray will depend on the ratio of distances between the gamma-ray source, pulsar or magnetar and the Earth. If the gamma-ray source is extra-Galactic, then the scattering of emission flux by the pulsar or magnetar gravitational and magnetic fields will be large. Thus, the emission intensity, which underwent significant bending of a ray, will be very small in the vicinity of the Earth. In this case the effect of ray bending will be revealed only as the harsh falling of detected emission intensity even by the disappearingly small value of the ray bending angles.

If gamma-rays were emitted near a magnetic neutron star (for example, if it is part of a binary system, or the gamma-ray sources are the regions, jointed to its surface), then scattering of this emission flux by the gravitaional and magnetic fields will not be so pronounced. In this case, although the emission intensity detected near the Earth will decrease with growing of the bending angle, it will not be so harsh as in the case of the extra-Galactic source. Thus, for astrophysical objects containing a neutron star with magnetic field at the level of $B \sim 10^{13} - 10^{15}$ G, effects of non-linear and gravitational bending of a ray will be assessible by observation even at the modern accuracy level using the extra-Terrestrial astronomy technique.

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